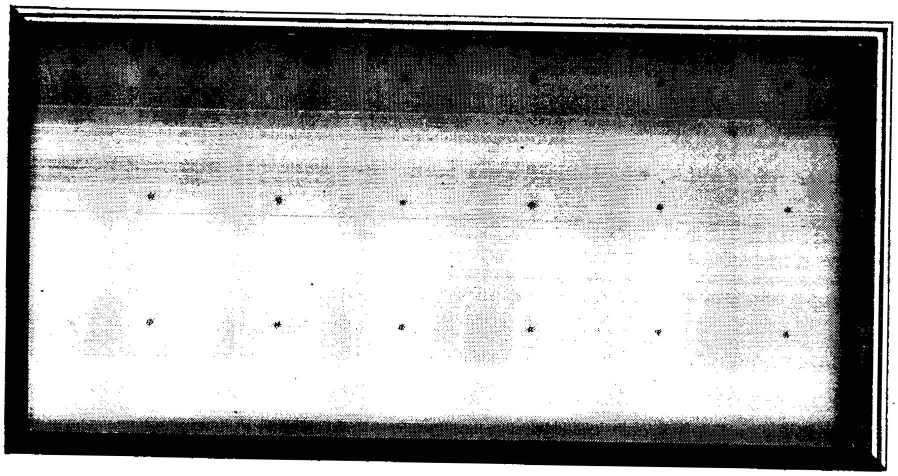
RECEIVED - 10/17/67
MS-DV-SE000184R
C01

MISSILE AND SPACE DIVISION



VOYAGER

GENERAL ELECTRIC

GPO PRICE $ ____________

CFSTI PRICE(S) $ ____________

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

RECEIVED
MAR 1968
NASA STI FACILITY
INPUT BRANCH

FACILITY FORM 602

N68-19092 (ACCESSION NUMBER)

(THRU) 1

53 (PAGES)

(CODE) 08

CR-93555 (NASA CR OR TMX OR AD NUMBER)

(CATEGORY)

GENERAL ELECTRIC

DIN 67SD4379
16 OCTOBER 1967

FINAL REPORT
VOYAGER SPACECRAFT
PHASE B, TASK D

VOLUME IV (BOOK 3 OF 5)

CENTRAL COMPUTER

PREPARED FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER

UNDER MSFC CONTRACT NO. NAS8-22603

GENERAL ELECTRIC
MISSILE AND SPACE DIVISION
Valley Forge Space Technology Center
P.O. Box 8555 • Philadelphia 1, Penna.

VOLUME SUMMARY

The Voyager Phase B, Task D Final Report is contained in four volumes. The volume numbers and titles are as follows:

Volume I	Summary
Volume II	System Description
Book 1	Guidelines and Study Approach, System Functional Description
Book 2	Telecommunication
Book 3	Guidance and Control Computer and Sequencer Power Subsystem Electrical System
Book 4	Engineering Mechanics Propulsion Planet Scan Platform
Book 5	Design Standards Operational Support Equipment Mission Dependent Equipment
Volume III	Implementation Plan
Volume IV	Engineering Tasks
Book 1	Effect of Capsule RTG's on Spacecraft
Book 2	Applicability of Apollo Checkout Equipment
Book 3	Central Computer
Book 4	Mars Atmosphere Definition
Book 5	Photo-Imaging

TABLE OF CONTENTS

LIST OF TABLES

SECTION 1
SUMMARY

1.1 PURPOSE

In order to perform the Voyager mission, there are many on-board functions that may be accomplished by digital processing of electrical signals. The purpose of this central computer study was to assess the relative merits of a centralized (Central Computer) approach versus a decentralized (Separate Subsystem) approach to implementing applicable functions.

1.2 SCOPE

In studying the relative merit of the two design approaches, we have chosen to compare (numerically, where feasible), the performance of "Separate Subsystem" and "Central Computer" systems implemented with comparable electronic techniques and degrees of redundancy to perform the same functions. The functions have been limited to those contemplated for the Voyager 1971 mission in the Task B study plus readily available examples of additional functions to represent growth to missions for 1973 and beyond. Competitive implementations for nine combinations of degrees of applied redundancy and functional complexity have been evaluated. The result is an indication of relative merit which can be used as a reasonable guide to a final decision along with other qualitative engineering factors.

1.3 CONCLUSIONS

The results of the numerical analysis suggest by a small margin that the separate subsystem approach is more favorable for the Voyager-oriented functions assumed and for the particular emphasis placed on the judgement criteria.

During the course of the study, many facets of both approaches were explored. In our consideration of the Central Computer approach excellent contributions were made by the Federal Systems Division of IBM and appear as appendices to our Milestone Report VOY-D3-TM-22.

Analysis of the details contributing to the evaluation for all cases considered indicates that the effect of economies in power, weight, and size for the Central Computer approach do not fully offset the inherent reliability of the separate subsystem approach.

These considerations, coupled with engineering judgement, lead us to recommend that present Voyager concepts not adopt a Centralized Computer approach. The relatively small margin of favor suggests that for future Voyager missions in which functions of significantly increased complexity may be contemplated, the question can logically be reopened.

SECTION 2
INTRODUCTION

2.1 CENTRALIZATION VS DECENTRALIZATION

In the general field of digital processing (indeed in the development of many physical systems), there are many closely related tasks to be performed. The choice logically arises between performing them either with a number of special purpose, decentralized devices or with one general purpose, centralized device.

In a fortuitous situation there may be, say, N identical tasks, the required timing of which will permit their being performed by one instead of N equipments. The N-fold potential savings in power, weight, and size are justification for exploring the matter further. If the tasks are not identical and should perhaps require coincidence of timing, the central equipment grows more complex. Even so, the somewhat less than N-fold potential savings may still lend encouragement.

For situations in which long-life reliability is important, the possibility that a failure in the central equipment may interrupt all functions must be considered. Only one function can be interrupted by a failure in a decentralized equipment. Other considerations include flexibility, testability, interface complexity, and ease of engineering, development, and manufacture.

In such a complex situation, the choice between design approaches is not readily apparent. Many of the factors needed for decision defy numerical evaluation. Indeed, some compromise may be in order.

2.2 CENTRAL COMPUTER VS SEPARATE SUBSYSTEM APPROACH FOR VOYAGER

The same choice between a central computer and a number of separate subsystems must be made for the digital processing tasks in the Voyager spacecraft. As spacecraft digital processing functions become more numerous and complicated, and advances occur in the spaceborne general purpose computer field, the economics of centralizing many pieces of equipment become more attractive.

Typical functions capable of digital processing include ground commands, telemetry signals, and the properly timed initiation of various spacecraft events. Individual digital functions have been principally associated with the following spacecraft subsystems:

a. Guidance and Control

b. Telemetry

c. Command

d. Data Automation Equipment

e. Computer and Sequencer

The functions of these subsystems have generally been implemented through separate special purpose devices.

In this study, we have developed a method of numerical evaluation to aid in the determination of the relative desirability of adopting a centralized computer approach. Because of the difficulty in evaluating many subtleties behind the criteria, the numerical evaluation must be used with other qualitative engineering factors in arriving at a decision.

2.3 GENERAL APPROACH

The main tasks of the study have been: 1) to determine functional requirements against which the performance of competitive implementations may be measured; 2) to synthesize separate subsystem and central computer systems for nine combinations of functional complexity and applied redundancy; and 3) to perform a comparative evaluation leading to an indication of relative merit. The work in these and supporting tasks, coupled with an interpretation of the results are presented in the following sections.

In general, the approach has been to arrive at an overall evaluation from a number of individual evaluations, each weighted in accordance with its importance. The evaluations together with the assumptions made are exposed for ready review and change. In the processing, inaccuracies present in the individual evaluations tend to average out in the combined result.

SECTION 3

REPORTS OF STUDY TASKS

3.1 LISTING OF FUNCTIONS TO BE PERFORMED

During this task, the list of functions was selected for which the competitive approaches were evaluated. They are listed in Table 3-1, together with a complexity and importance rating described in Section 3.1.1. Functions 1 through 11 were those identified in the Task B Study and described in the Voyager Phase IA, Task B, Spacecraft Functional Description, Volume A. They represent groupings of associated subfunctions as noted in the table. Functions 12 and 13 represent a current concept of (Science) Data Automation Equipment operation based on the scientific experiments described in Section 3.1.2 and listed in Table 3-2. Functions numbered 14 and higher represent additional functions selected in a supporting task described in Section 3.2.

Table 3-1. List of Functions

Function	Complexity	Importance
1. Process Ground Commands	3.0	0.9
a. Demodulate and error check ground command data bits.		
b. Decode discrete commands and send to subsystem user.		
c. Decode quantitative commands and send to subsystem user.		
2. Provide G&C Logic and Switching Control	0.012	0.6
a. Establish G&C mode of operation by proper interconnection of components.		
b. Indicate sun presence by monitoring the pitch and yaw regenerative clippers and the sun gate amplifiers.		

Table 3-1. List of Functions (Cont)

Function	Complexity	Importance
c. Indicate sun acquisition by monitoring fine sun gate amplifier.		
d. Indicate star acquisition when roll rate and position signals are nulled.		
e. Provide signals to turn on the 400 Hz inverters and all gyros in the rate mode when an attitude reference is lost.		
f. Provide signals to enable or disable the pneumatic drivers as a function of signals from the gyro temperature logic which indicate whether the gyro wheels are energized.		
3. Process Telemetry Data	0.19	0.9
a. Commutate analog data.		
b. Encode analog data.		
c. Shift real-time digital data into accumulator.		
d. Shift data to transfer register.		
e. Select data source.		
f. Provide format control.		
4. Inititate Time-From-Launch Functions	1.4	0.3
a. Provide non-critical discrete commands.		
b. Provide quantitative commands.		

Table 3-1. List of Functions (Cont)

Function	Complexity	Importance
5. Initiate Computed Functions	0.11	0.3
a. Provide commands to step high-gain antenna gimbals.		
b. Provide commands to step PSP gimbals.		
6. Initiate Time-To-Go Functions	0.24	0.9
a. Provide trajectory correction commands.		
b. Provide c[illegible] insertion commands.		
c. Provide spacecraft-capsule separation commands.		
d. Provide 180° roll re-orientation commands.		
7. Initiate Periodic Orbital Functions	0.14	0.6
a. Provide PSP turn on/off commands.		
b. Provide signals based on Gimbal E angle.		
8. Provide C&S Data to Telemetry Subsystem	0.094	0.6
a. Provide memory word and address.		
b. Provide multiplexed TTG word.		
c. Provide C&S status word.		

Table 3-1. List of Functions (Cont)

	Function	Complexity	Importance
9.	Provide Occultation Signals	0.25	0.3
	a. Provide for earth occultation.		
	b. Provide for sun occultation.		
	c. Provide for Canopus occultation.		
10.	Provide Data Storage Capability	60	0.6
	a. Store engineering data.		
	b. Store cruise science data.		
	c. Store planetary science data.		
11.	Perform PSP Gimbal E Local Vertical Tracking	0.11	0.6
	a. Track local vertical.		
	b. Re-cycle PSP Gimbal E during non-science taking portion of orbit.		
	c. Provide Gimbal E output pulses.		
12.	Provide Control of Experiments	3.0	0.9
	a. Receive sensor sequencing information from Computer and Sequencer Subsystem (C&S)		
	b. Receive commands (discrete and quantitative) from Command Subsystem and C&S. Decode these commands and execute when required.		
	c. Provide calibration and on/off sequence for each sensor as determined by 1 and 2.		

Table 3-1. List of Functions (Cont)

	Function	Complexity	Importance
	d. Provide experimental parameter sequencing control.		
	e. Provide sample pulses as required.		
13.	Process Scientific Data	3.0	0.9
	a. Commutate analog data.		
	b. Encode analog data.		
	c. Provide buffering of data.		
	d. Provide format control.		
14.	On-Board Checkout (Active)	1.5	0.6
15.	Data Compression		
	a. Zero order prediction	0.5	0.6
	b. First order partial interpolation	1.0	0.6
16.	Error Correction Coding	0.015	0.3
17.	Approach Guidance	0.18	0.3

Table 3-2. Assumed Scientific Experiment Parameters

Sensor No.	Sensor	Bit Rate	Intermittent	Coverage	Total Orbit Data (bits/orbit)
1	IR RAD	2300 bps	Yes	$\pm 60^{o}$ from Periapsis	$8x10^{6}$
2	UV SPEC	High 2500 bps	Yes	Entire Orbit	6.3×10^{7}
		Low 130 bps	No	Entire Orbit	$2.5x10^{6}$
3	HRIR SPEC	150 bps	No	200^{o} Centered at High Noon	10^{6}
4	BBIR SPEC	2000 bps	Yes	Entire Orbit	$5x10^{7}$
5	HIGH RES TV	$5.4x10^{6}$ bps	Yes	15 Frames/Orbit	$8x10^{8}$
6	MED. RES TV	$5.4x10^{6}$ bps	Yes	15 Frames/Orbit	$8x10^{8}$
7	MED. RES TV	$5.4x10^{6}$ bps	Yes	15 Frames/Orbit	$8x10^{8}$

3.1.1 COMPLEXITY AND IMPORTANCE RATING

Because of the inherent complexity of a general purpose digital computer, it is intuitively expected that the balance of favor will swing from the separate subsystem approach toward the central computer approach as the functional complexity of assigned tasks increases from very low to very high. It has been instructive to explore this trend by varying the included complexity of a functional grouping. As an aid to determining the choice of functional groupings, a complexity rating has been assigned to each function, as noted in Table 3-1. For digital logic functions, it appeared reasonable that functional complexity might well be represented by the failure rate of a single-string, or nonredundant, implementation. It was assumed that the failure rate of a simplex implementation could also be used as a measure of complexity for other functions. Accordingly, the complexity rating shown is the estimated simplex failure rate in percent per thousand hours.

Three functional groupings of included complexity were selected:

a. Minimal: Functions 1-13,

b. Intermediate: Functions 1-13, 15a, 16, 17,

c. High: Functions 1-14, 15b, 16, 17.

The minimal grouping includes the Task B and DAE functions -- those basic to the Voyager mission of Task B. The other groupings also include selected examples of the additional functions as noted.

The importance ratings listed in Table 3-1 are estimated functional importance ratings ranging from low at zero to high at unity. Each rating is based on the consequences of nonperformance of its function assuming all other functions are performed.

3.1.2 DATA AUTOMATION EQUIPMENT FUNCTIONS

Science data handling functions are performed by the Data Automation Equipment (DAE). These functions were not a subject of the Task B study and, therefore, are described in this report in greater detail. In general, the DAE must be capable of accommodating late changes in the science instruments and their operation to assure taking advantage of the latest scientific developments prior to launch. In this sense, the DAE serves as a buffer to bring the experiment requirements into consonance with the remainder of the spacecraft, the definition of which must be established earlier in the mission development.

The DAE will provide detailed control of each experiment and prepare the experimental results for subsequent storage or transmission. The DAE functions listed in Table 3-1 are considered to be representative of those to be required in an actual 1973 Voyager spacecraft, even though the experiment definitions on which they are based (Table 3-2) are probably transitory.

The following descriptions pertain to the subfunctions of providing control of experiments, function 12:

a. Signals received from the C&S Subsystem will consist of terminator crossing times, time code, and other timing pulses referenced to the terminator crossing. These signals will be used to determine the proper time to turn on/off the various instruments and execute timed commands.

b. The commands received from the Command Subsystem will be decoded, stored until time for execution, then executed.

c. The sequencing of each instrument is programmable, i.e., it is controlled by the stored commands discussed in b above. In the absence of stored commands, a fixed instrument sequence will be employed.

d. The DAE will provide signals to change mirror positions, optical filters, shutter speeds, etc., when necessary.

e. Sample pulses defining the time at which the data should be quantized on an element-by-element basis will be provided.

The following paragraphs pertain to the processing of scientific data, function 13.

The output data from the instruments will be conditioned to provide compatibility with the logic levels, data rates, and timing of the DAE. This will include such things as commutating when an instrument has two or more output channels, converting from analog to digital data if analog data is received, and buffering (delaying) if the data rate or reception time is incompatible.

The output formats presented to the Data Storage Subsystem are programmable, i.e., the format is subject to change as a function of the instrument sequencing discussed previously. In addition to the actual data, the formats will include instrument identification and the time the data were taken. Signals required by the Data Storage Subsystem to properly store the formatted data will be provided by the DAE.

3.2 SELECTION OF ADDITIONAL FUNCTIONS

The first 11 functions of Table 3-1 are those identified in the Task B Study. Functions 12 and 13 are (Science) Data Automation Equipment functions. These are basic to the Voyager mission. The remainder are additional functions selected in recognition of potential updated requirements, technological advances, and previously excluded functions which might be made feasible by the availability of an on-board central computer.

In this task, readily available examples of the listed additional functions were selected. The purpose was not to recommend these particular functions for the Voyager mission, but to provide additional functional complexity through examples representative in type and complexity.

3.2.1 ON-BOARD CHECKOUT (ACTIVE)

A concept described in a paper by Larsen and Skinner[1] was selected as an example of the automatic checkout function. The concept is summarized in that paper as follows:

> "... a data link terminal associated with a central computer complex accepts instructions from the computer for transfer to the test set and transfers test results from the test set to the computer. Control of the test set is based on a universal memory concept; that is, all equipment to be controlled has a small memory associated with it. Instructions are routed to, and stored in these memories, for decoding upon an execute command. This concept provides for unlimited expansion for stimuli or switching matrices.
>
> Measurement and evaluation of test results is performed in digital format to benefit from the higher accuracies attainable. Analogs are converted to frequency by a highly stable voltage to frequency converter.
>
> The data link is two-way, i.e., instructions can be transferred to the test set while responses are transferred to the computer. The data link reports status of message processing at the computer complex, also."

3.2.2 DATA COMPRESSION

The general goal of data compression is to eliminate all data which are not essential to the recognition of the intended message within some acceptable tolerance. It is probable that image forming sensors will yield the bulk of the data for which compression may be desirable.

Two examples of data compression were selected. The first was zero order prediction in which the procedure is to transmit only those data samples which deviate from a predicted value by more than an acceptable tolerance. When a sample is sensed as significant, it is transmitted and used as the predicted value until the next significant sample replaces it.

The second example was initially planned to be a first order interpolator, however, the exigencies of selection resulted in a partial interpolator. The example chosen was taken from a paper by Massey and Smith(2). In this paper, the algorithm is identified as First Order, Variable Corridor, Artificial Preceding Sample Transmitted (FVA). A non-redundant sample is one which falls outside a predicted corridor by more than a preset tolerance range. Upon occurrence, the predicted value of the preceding sample is selected as the finish of the preceding straight line interpolation and the start of the next line segment. The corridor for the next sample is determined by straight lines from the new artificial preceding sample through the end points of the non-redundant sample tolerance range. The corridor is reduced by moving one or both lines inward (as possible) to the tolerance range ends of succeeding redundant samples. This algorithm is considered to be only partially interpolating since the start point for a line segment is determined not with the end point of that segment, but by a (non-redundant) sample point occurring only one sampling interval beyond the start point.

In both algorithms, the significant samples emerge at a non-uniform rate. It is generally advantageous to time tag each sample and establish a uniform bit rate using a buffer memory. The degree of compression obtainable is a function of the tolerance selected and the nature of the data. Compression ratios for image data from these algorithms can be expected to be in the vicinity of 3 to 5.

3.2.3 ERROR CORRECTION CODING

Whereas data compression techniques remove unwanted redundancy from data to be transmitted, error control coding introduces redundancy for the express purpose of improving the error rate at the output of the receiver. The error rate dictates the spacecraft-radiated power if the other characteristics of the transmission link are known. The example selected offers about a 3 db performance improvement for a threshold decoded word error probability of 3.5×10^{-2}. This performance improvement can be utilized in a reduction of transmitter power, reduction of antenna size, or increase in data rate in any balance as dictated by system tradeoff considerations.

During the Phase IA Task B Voyager study during late 1965, a 63, 7 (7 data bits, 56 redundant bits) "regular bi-simplex" code was selected as a promising error control coding system. This system still represents a judicious choice for consideration in application to the 1973 Voyager mission. This system and its performance is described in some detail in a report by Huffman[3].

The coding system operates by designating a 63-bit word for each block of seven bits presented to it. The 2^7 words are generated by a linear feedback shift register. The correlation between any two different words is 1/63, -1/63, or -1. Detection is accomplished at the receiver by correlating the recieved 63-bit word with every possible word in the vocabulary. The possible word having the greatest correlation with the received word is selected as the word which was transmitted.

3.2.4 APPROACH GUIDANCE

Planetary approach guidance is currently accomplished by utilizing Deep Space Network data for both the spacecraft and target ephemerides. Calculations indicate that a measurement of the attitude of the line of sight from the spacecraft to the target can be of significance in improving earth-based tracking errors.

A means of making the line of sight measurement is discussed in a paper by Seaman and Brown[4]. In this means, images of the target planet, Canopus, and the Sun are projected onto the face of a vidicon such that the positions on the face determine their actual positions with respect to the spacecraft. One point each is used to locate the Sun and Canopus. Six points on the planet disc are used to locate the planet. Each point is coded into a 20-bit word; 160-bits serve to define the relationship for each frame. These bits are transmitted to earth for utilization.

3.3 SURVEY OF COMPUTER DEVELOPMENT

In order to arrive at practical Central Computer implementations, comparisons to presently available computers are desirable. A survey of computer development has been made to provide a realistic and diverse capability base for a careful practical extrapolation of the many functional and physical parameters needed to adequately describe Central Computer forms for the study.

Data have been compiled on many general purpose computers which are at least in the development model stage. The sources have been manufacturer's data and a summary as prepared by Liviakis and Firstman[5]. Computers considered were those for which weight and power were below 100 lb and 300 watts, respectively, corresponding to anticipated Voyager allowances. In general, the environmental class was set at meeting specification MIL E-5400 or better and aircraft computers were not excluded. The computers included are listed in Table 3-3.

Table 3-3. Computers Included in Survey

Autonetic D26C	Hughes HCM 206	Litton L-3040
Autonetic D26J	IBM 4π-TC	Litton L-3050
CDC 5360	IBM 4π.-CP	Litton L-3060
CDC 5400	IBM 4π-EP	Northrup NDC-1051
CDC 5400-8	IBM LVDC	TRW 448
Honeywell Alert	Litton L-304	Univac 1824-C
Honeywell Sign III	Litton L-305	Univac 1830-A
Hughes HCM 205	Litton L-306	Univac 1818

Of the computers surveyed, three have been selected as representative of the general class of computer compatible with anticipated Voyager functional requirements. These are the IBM 4π-TC, Autonetic D26J, and IBM LVDC. Typical descriptive parameters of these computers are included in Table 3-4. It is emphasized that we are not now

Table 3-4. Characteristics of Selected Contemporary Computers

Parameter	Computer Type		
	IBM 4π TC	Autonetic D26J	IBM LVDC
Parallel/Serial	P	P	S
Rated Speed μsec	20	18.3	190.1
Add Time μsec	15	12	82
Multiply Time μsec	51	42-54	328
Instruction Set	54	27	18
Mem* Capacity (10^3 words)	8	16	4 x 32
Mem Word Size (bits)	8	12-16	26
I-O Form**	Q, PR	A, D, Q	Q
I-O Speed 10^3 (wps)	80 Burst	13.8	12
Weight (lb)	17.3	20 w/o IO	78.5 w/o IO
Volume (in.^{3})	640	363 w/o IO	3800 w/o IO
Peak Power (watts)***	60	62	142 w/o IO
Reliability Estimate	7.5 K MTBF Hrs	18.0 K MTBF Hrs	25.0 K MTBF Hrs

* Without Science and Engineering Data Store.

** Legend: A - Analog Level, D - Discretes; Q - Digital Word Quantitative; PR - Pulse Rate; I - Incremental Pulse; ALL - All of the Above

*** Without Auxiliary Data Storage.

recommending any existing computer for use on Voyager. Indeed, it is doubtful that any existing computer will be a perfect match for the Voyager requirements; neither are we excluding any other computers of the appropriate class from further consideration.

These computers represent a diverse capability in their class and were selected in part because of their advanced state of development and history of successful use which lend greater confidence in manufacturer's data than for some computers in earlier stages of development. All three use microelectronic elements extensively.

3.4 DEFINE "SEPARATE SUBSYSTEM" SYSTEM DESIGN

In the Separate Subsystem approach, each of the functions is implemented by a separate device as indicated in the Task B Study or the description of the function (Section 3.1). In general, the parameters of each implementation have been determined or estimated only as required for the evaluation; in the interest of efficiency, parameters having no effect on the numerical result have not been evaluated. In some instances the parameter values appear only in the pertinent Functional Performance Index Evaluation tables of our Milestone Report VOY-D3-TM-22[6].

The application of redundancy to the separate subsystem implementations of the functions under consideration is described briefly in Table 3-5. Functions 1 to 11 are functions performed by subsystems defined during the General Electric Phase IA Task B Study and are also among the functions considered during the General Electric Task C Redundancy Study. For most of these functions one or more alternative redundancy forms (in addition to the Task B redundancy form) were considered during the Task C study. For functions 1 to 11, the recommended redundancy of Table 3-5 is the Task B redundancy form. The maximum redundancy is that redundancy form resulting in the greatest weight addition to each functional implementation. Note that it is not necessarily the form resulting in the highest reliability. One consideration in the selection is that operation without interruption is provided by triplication with voting in the event of a failure in a simplex unit whereas, in a duplex arrangement, the failure interrupts operation until corrective action can take place. In a number of instances the recommended and maximum redundancies are identical.

The recommended redundancy for functions 12 to 17, implementations of which are not defined in the Task B or Task C studies, is that which might be expected to provide best performance based on Task C results. The maximum redundancy indicated for these functions is considered to be in excess of that required for best performance in light of the Task C results.

Table 3-5. Applied Redundancy for Separate Subsystem Functional Implementations

Function	Recommended Redundancy	Maximum Redundancy
1. Process Ground Commands	Duplication of simplex configuration. One unit operating at a time.	Same as recommended configuration.
2. Provide G&C Logic and Switching	Duplication of simplex configuration. One unit operating at a time.	Triplication of simplex configuration; voting.
3. Process Telemetry Data	Selective addition of spare units. Simplex commutator. Spares turned off until needed.	Back-up spares for all units including commutator. Spares turned off until needed.
4. Initiate Time-From-Launch Functions	Selective duplication and triplication with voting. Simplex memory.	Selective duplication and triplication with voting. Dual memories (both operating).
5. Initiate Computer Functions	Selective duplication to protect against runaway condition. Mainly non-redundant.	Same as recommended configuration.
6. Initiate Time-To-Go Functions	Triplication with voting. Addition of time back-up for liquid engine turn off.	Same as recommended configuration.
7. Initiate Periodic Orbital Functions	Selective duplication to protect against runaway condition. Mainly non-redundant.	Same as recommended configuration.
8. Provide C&S Data to Telemetry System	Simplex configuration.	Same as recommended configuration.
9. Provide Occultation Signals	Simplex configuration.	Duplication of simplex configuration.

Table 3-5. Applied Redundancy for Separate Subsystem Functional Implementations (Cont'd)

Function	Recommended Redundancy	Maximum Redundancy
10. Provide Data Storage Capability	Duplication of playback sequencer and power supply, spares turned off until needed. Otherwise, nonredundant.	Same as recommended configuration.
11. Perform PSP Gimbal E Local Vertical Tracking	Simplex configuration.	Duplication of simplex configuration. One unit operating at a time.
12. Provide Control of Experiments	Duplication of simplex configuration. One unit operating at a time.	Triplication of simplex configuration with voting.
13. Process Scientific Data	Duplication of simplex configuration. One unit operating at a time.	Triplication of simplex configuration with voting.
14. On-Board Check-out (Active)	Selective duplication and triplication with voting.	Duplication of simplex configuration. One unit operating at a time.
15a. Data Compression--Zero Order Prediction	Triplication of control logic with voting. Simplex memory.	Triplication of control logic with voting; duplication of memory (one memory operating at a time).
15b. Data Compression--First Order Partial Interpolator	Triplication of control logic with voting. Simplex memory.	Triplication of control logic with voting; duplication of memory (one memory operating at a time).
16. Error Correction Coding	Duplication of simplex configuration. One unit operating at a time.	Triplication of simplex configuration with voting.
17. Approach Guidance	Duplication of simplex configuration. Both units operating.	Triplication of simplex configuration with voting.

3.5 DEFINE "CENTRAL COMPUTER" SYSTEM DESIGN

In order to make the required comparisons between "Separate Subsystems" and "Central Computer" approaches to the Voyager requirements, it has been necessary to synthesize Central Computer systems in sufficient detail for the comparison. The system concepts arrived at for central computer implementations were based on functional requirements identical to those of the separate subsystem studies. They are described in Section 3.1.

It would have been possible in this study to select, from those examined in the survey (Section 3.3), a basic computer which could functionally perform the tasks required. This was not done, however, for several reasons. To apply an "off-the-shelf" computer, there would undoubtedly be extensive "customized" input-output equipment to be developed. This consideration and varying degrees of mismatch between the computer capability and Voyager requirements leaves open to question the probability of satisfactory reliability, physical and electrical efficiency, and functional flexibility. On the other hand, more programming, testing, and reliability experience would probably exist; the development lead time would undoubtedly be shorter; and money would probably be saved on development cost of computer and test equipment. Nevertheless, because of the extreme reliability requirements, it was deemed best to establish computer forms specifically suited to the functional requirements with the best feasible reliability. To do this and still maintain desirable reality in the estimated parameters of the computer forms, the surveyed computers were examined and comparisons were made. As reported in Section 3.3, it was possible to evaluate a sizeable number of contemporary computers in various stages of development. Some consideration was also given to the possibilities offered by more sophisticated multiprocessing, and distributed processing techniques, however, the development of these techniques is in an early stage. Since the needs of Voyager are more or less immediate, extrapolations to what might exist in the mid 1970's were not made but rather only to the end of the 1960's. As a result, prime interest centered on simplex forms, their use in duplex and triplex arrangements, and in a combined multiple computer form called Triple Modular Redundancy (TMR).

Surveyed computers seemed to offer quite a few positive points. On the negative side, however, many questions still remain. Some of these are:

a. Do reliability estimates include input-output equipment?

b. What is the definition of a failure?

c. Do reliability results benefit from in-service preventive maintenance?

d. Is the input-output system included in statements of physical characteristics?

e. Are electrical interfaces to other subsystems electrically dc isolated?

f. Is the computer cooled by air, water, glycol, or a cold plate?

g. Is the computer capable of being loaded and tested via umbilical class connections?

h. What happens to in-process computations following a short or long term power fault?

i. How difficult is the programming task?

These are some of the more important questions to answer in a computer selection and they have been considered in the computer forms of this study. The following list forms a set of ground rules for consideration:

a. Reliability estimates will include Input-Output (IO) equipment.

b. A failure consists of false data, or misrouted data, or the absence of expected data. All failures are not of the same consequence. Failures that can be compensated for by ground data link are of least importance. Those not compensable are of high importance, and if they can result in mission abort they are of prime importance.

c. No post-launch maintenance is possible except via ground link circumventing a problem, or by automatic in-flight checkout means (a function added to basic functions).

d. Input-Output and local power transformers, rectifiers, and filters are included in physical estimates.

e. All external data interfaces of the computer are dc isolated to contain electrical failures within the failed subsystems.

f. The computer is cooled by conduction to a cold plate, or by liquid to a heat exchanger, or a combination of both.

g. The computer is capable of having its memory loaded via an umbilical, operated in all modes, and its memory read out. It is further desirable to have a high speed step through exercise of flight sequence not to exceed 4 or 5 hours for the total sequence. All inputs and outputs from principle computer subsystems shall be capable of monitoring via umbilical connections.

h. The computer shall complete to storage a computation in progress during a power interruption. A predetermined data recovery technique shall be exercised following the restoration of power.

i. Programming should make use of assembler programs and be capable of simulation on ground computers available to operational and maintenance personnel. Programs should be as simple and unbranched as possible, adaptable to change in a relatively short time, and readily testable. Science programs should be as independent of sequencing programs as possible to allow independent modification.

j. The computer shall use microelectronics whenever they can supply reliability equal to, or better than, discrete parts.

k. A non-destruct readout memory will be used.

l. A method of knowing mission real time is required either by a real-time clock or by integration of preselected time increments.

m. Energy shall be conserved by a computer standby-wakeup feature where possible. All power estimates are given as peak power to show the need if served by solar panel power alone without battery backup.

In examining the requirements for the Voyager computer, it is readily apparent that there is a diverse mix of timer-like sequencing (flight program) tasks; data (engineering and science) selection, storing, formatting and reading out in relatively large quantities with few computations required; multiplexing or switch sorting selection (telemetry data input); decoding of digital words (command decoding); pulse rate outputting (PSP and HG antenna articulation) with very modest computation; and sequencing of periodic orbital functions. One finds a minimum of actual computation required in the basic functions, and a maximum of data management. As a result, the basic requirements are for only a rudimentary arithmetic unit, a very modest program storage, and a very sizeable Input-Output section. The computer portion should have many of the "general purpose" characteristics in modest amounts, however as a whole, the unit is more aptly described as a "centralized data processor."

Of the surveyed computers, three are taken as representative of a breadth of functional capabilities. The representative computer plus the computers synthesized in this task, designated C_1 through C_9 are listed with primary characteristics in Table 3-6. These are different configurations of computers prepared to correspond functionally to separate subsystem forms S_1 through S_9. The relationship of one C_n form to another is shown in Table 3-7.

Forms C_1, C_4, and C_7 are simplex computers without redundancy (and are not recommended for the Voyager mission because of relatively poor reliability).

Forms C_2, C_5 and C_9 contain a degree of redundancy recommended as most compatible with Voyager requirements. Further costly redundancy is not expected to provide comparable further improvement in reliability. This series contains the techniques of redundancy implemented in the Saturn V LVDC computer. Logic is Triple Modular Redundant, and the memory is duplex. In addition, the Input-Output and power systems are duplexed.

Forms C_3, C_6, and C_9 contain a degree of redundancy in which there is a full TMR configuration. There is extensive voting through the stages of the three computers, memories, I-O, and power supplies. There is some reliability gain but at a high price.

In Table 3-7, as one goes from level C_1 to C_4 to C_7, the functional complexity increases as noted by the added functions. As the complexity increases, one may observe in Table 3-6 that the rated speed is increased (but still is very slow), multiplication is incorporated, the instruction set increases, the memory capacity is expanded, the I-O rate is increased and the distribution system broadened, and physical parameters increase. The steps from C_1 to C_4 to C_7 levels are relatively modest but are believed to span the probable Voyager task extensions.

Of the forms in the Tables, C_2, C_5, and C_8 are believed to be the most suitable in terms of applied redundancy. The Voyager requirements have in the past dictated the complexity level of which C_2 would be most appropriate. As requirements are added, the complexity level of

Table 3-6. Primary Characteristics of Synthesized and Reference Computers

Parameter \ Computer Type	IBM 4π TC	Autonetic D26J	IBM LVDC	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Parallel/Serial	P	P	S	P	P	P	P	P	P	P	P	P
Rated Speed (μ sec)	20	18.3	190.1	260	260	260	28	28	28	17	17	17
Add Time (μ sec)	15	12	82	100	100	100	10	10	10	5	5	5
Multiply Time (μ sec)	51	42-54	328	None	None	None	1msec	1msec	1msec	500	500	500
Instruction Set	54	27	18	16	19	20	24	27	28	35	38	39
Memory* Capacity (10^3 words)	8	16	4 x 32	1 x 2	2 x 2	3 x 2	1 x 4	2 x 4	3 x 4	1 x 8	2 x 8	3 x 8
Memory Word Size (bits)	8	12-16	26	18	18	18	18	18	18	18	13	18
I-O Form**	Q,PR	A,D,Q	Q	All	All	All	All	All	All	All	All	All
I-O Speed (10^3 wps)	80-Burst	13.8	12	5	5	5	67	67	67	67	67	67
Weight (lb)	17.3	20 w/o IO	78.5 w/o IO	31	81	88	37	89	97	49	101	111
Volume (in.^{3})	640	363 w/o IO	3802 w/o IO	1500	2300	2700	1800	2450	2820	2200	2600	2950
Peak Power*** - (watts)	60	62	142 w/o IO	42	105	116	47	112	123	49	116	127
Reliability Estimate Without Tape Units (Hrs-MTBF)	7.5K	18.0K	25.0K	62K	78K	82K	51K	71K	75K	46K	66K	69K

* Without Science and Engineering Data Store.

** Legend: A = Analog Level; D = Discretes; Q = Digital Word Quantitative; PR = Pulse Rate; I = Incremental Pulse; All = All of the above.

*** Without auxiliary data storage.

Table 3-7. Designation and Description of Synthesized Computers

C_1 Simplex - Lowest Speed - Minimum Store, Add Only. Functions 1 - 13.	C_2 TMR Logic - Duplex Memory, I-O, and Power Supply -- Functionally similar to C_1.	C_3 TMR Logic, Memory, I-O & Power Supply - Functionally similar to C_1.
C_4 Simplex - Middle Speed - Memory Capacity, I-O, and Multiply added to C_1 - Programming more complex - Increased Duty Cycle - Functions 1 -13, 15a, 16 and 17.	C_5 TMR - Partial (as C_2) - Functionally similar to C_4.	C_6 TMR - Full (as C_3) Functionally similar to C_4.
C_7 Simplex - Fastest Speed - Memory Capacity, I-O, Multiply, added to C_1 - Functions greatly increase programming complexity - Functions 1 - 13, 14, 15b, 16 and 17 - High duty cycle.	C_8 TMR - Partial (as C_2) Functionally similar to C_7.	C_9 TMR - Full (as C_3) - Functionally similar to C_7.

C_5 is likely to be reached in which case C_5 would be the recommended computer form if it is reliable enough in its handling of critical functions.

During the study an example of computer design was prepared and discussed in considerable detail by the Federal Systems Division of IBM. This example is appended to our Milestone Report VOY-D3-TM-22[(6)]. It is considered to be a very suitable and substantial description of a C_5 computer.

3.6 REVIEW OF REDUNDANCY TECHNIQUES

A key factor in the successful operation of a long-life, unmanned space vehicle of the Voyager class is the providing of adequate reliability in its design. Mission durations of up to two years have been discussed with a design goal for a 1973 Voyager mission set near one year. While specific reliability goals have not been assigned for all the implementations included in this study, it is expected that desirable MTBF values will be at least several times the mission duration.

One consideration in the comparison of the Separate Subsystem and Central Computer approaches is the manner in which reliability goals must be set. Reliability goals for individual implementations can be set commensurate with the criticality of the separate functions performed. By contrast, the reliability goal for the entire central computer will tend to be set by the single most critical function to be performed. Because of this consideration and the inherent complexity of general purpose computers, it is expected that the achieving of adequate reliability will be a key deterrent to their use in long duration space-borne applications for some time.

In all of the implementations it is assumed that the best available (end of 1968) piece parts and assembly practices will be utilized. Further contributions to reliability can come from the application of redundancy. The main concept is to provide alternate equipment to accomplish a particular task in the event of a failure. This can be accomplished in many different ways.

In general, reliability is gained at the expense of added size, weight, and power. In addition, the presence of necessary auxiliary circuitry for fault detection and location, switching and voting, with its own reliability considerations, tends to erode the potential gain in overall system reliability. The suitability of a particular redundancy technique must be evaluated in light of the requirements peculiar to the situation under consideration.

In this Central Computer Study, the application of several different types of redundancy has been considered in order to enhance the reliability of system implementations for the two competitive approaches. Specific applications to the implementations are discussed in Sections 3.4 and 3.5. There are many types and variations of redundancy techniques. A few of the more notable are briefly discussed here.

One common technique is simplex operation with switchable spares. In this technique, fault detection and switching circuitry is required. Changeover may be delayed by the need to set the spare to the operating condition. Application of redundancy at the unit* level requires a minimum of auxiliary circuitry, but differences in simplex reliability of sub-units are not recognized. Application at sub-unit levels permits recognition of sub-unit reliability differences and potential economies by providing a smaller number of spares for the more reliable sub-units. Potential benefits here are often reversed by the requirement for fault detection and switching circuits at the sub-unit level. Applications are favored by situations requiring relatively high powers and duty cycles.

For low power and low duty cycle situations, multiple operation may be attractive. In this technique, two units (or sub-units) are operated simultaneously. Faults are detected by simple comparators at the outputs. Some form of diagnosis is required so that the faulty

*For the purposes of this discussion, the term "unit" will refer to the totality of equipment required to accomplish a particular task in hand on a simplex basis.

unit can be switched out. Because the second unit is already operating, changeover is readily accomplished. An additional potential advantage over the switchable spare technique is that faults are more readily detected. On the other hand, the faulty equipment must be determined before disconnection; however, the auxiliary circuitry for this may not represent a significant penalty. It is possible to operate more than two units simultaneously. However, inasmuch as switching is required in any event, it is perhaps preferable to provide redundant units beyond the first as switchable spares. Considerations for application of multiple operation at sub-unit levels are similar to those for simplex operation with switchable spares.

A third technique is multiple operation with voting. In this technique, an odd number of units are operated simultaneously. The proper output is assumed to be that of the majority. Failure of up to, but not including, a majority of the units does not interrupt operations. The number of units is usually three in order to hold the power and weight at reasonable values. For many situations, sufficient reliability is attained with no switching and no auxiliary circuitry but the voter. One possible extension would be to detect and locate faults with simple comparators and then revert to simplex operation with spares or multiple operation.

An emerging technique, especially for computers, is that of multiprocessing. In this technique, multiple sub-units are available to perform the major computer functions. As the need arises, appropriate sub-units not being used at the time are selected for use by central control logic. Failure of all but one of a particular type of sub-unit will result in a slowing of the overall computer operation since some functions may have to wait for others to be accomplished. This type of malperformance has been termed "graceful degradation." This degraded mode of operation may be more attractive than an "all or nothing" capability. One apparent difficulty is in the complexity of the central control logic.

Related to these redundancy concepts is the concept of functional redundancy in which backup is provided by different equipment in which the required functions are implemented in a significantly different manner. For example, a particular function might be alternatively accomplished by analog or digital processes, preferably under circumstances where both processors were required for independent reasons. This concept also lends itself to degraded operation in backup modes.

In many instances, combinations of techniques are profitably applied. A number of redundancy techniques are discussed in the Voyager Task C Redundancy Study. Examples of redundancy in general purpose computers of capability compatible with an assumed Voyager mission are discussed in Appendix A of our Milestone Report VOY-D3-TM-22.[6] These examples were prepared for this purpose by the IBM Federal Systems Division. Relative changes in reliability (for assumed failure rates), power, weight,and size are calculated for several types of redundancy. The referenced data have been useful in estimating the parameters of competitive implementations of both approaches.

Three degrees of applied redundancy have been selected for each degree of included complexity as described in Sections 3.4 and 3.5.

3.7 PREPARATION OF EVALUATION CRITERIA

3.7.1 GENERAL APPROACH

In studying the relative merit of the two design approaches, a comparison is made of the performance of Separate Subsystem and Central Computer systems, implemented with comparable electronic techniques and degrees of redundancy to perform the same function. The list of functions from which groupings for implementation were selected is given in Section 3.1. The following is a discussion of the evaluation criteria and their application.

The general method consists of two main steps. In the first step, the performance of each particular system implementation is evaluated for each of the functions it is designed to accommodate. In the second step, the individual functional performance evaluations are combined to yield a total performance index for the systems under evaluation.

In the functional performance evaluation, the criteria (reliability, size, power, etc.) are identified and weighted. For each proposed implementation, the weighted and normalized sum of the numerical evaluation against each criterion represents the "goodness," or performance index of that implementation.

The performance of the total system implementation is determined by the weighted normalized sum of all the individual functional performance indices.

3.7.2 FUNCTIONAL PERFORMANCE INDEX EVALUATION

A Functional Performance Index Evaluation Chart is intended to show a number indicating relative performance of a function by a particular implementation. Any implementation represents some compromise of various criteria so as to approach optimum for the most valued criterion, therefore perfect performance is not obtainable and all performance numbers reflect this. The total degradation of performance is assessed as the sum of weighted normalized penalties for each of the criteria. Each criterion penalty is the product of the relative importance of the criterion for that function, and the "badness" of the implementation.

In order to arrive at "badness" measures for each criterion of an implementation, the question of what is good and what is bad immediately arises. In addition, there is the question of what kinds of units to use for each criterion. The answers to these questions are recognized as being quite arbitrary; accordingly, the units and ranges selected as a result of the study have been set forth in a manner suitable to a user's modification if he so desires. During the study, experienced judgement was applied to selecting units reflecting the most critical factors for a criterion, and to do this some units were specially derived. When establishing the limits of acceptable range for the units of a criterion, it was recognized that if the range was too broad, the contribution of the criterion could be improperly minimized. Further, it was recognized that the effectiveness of a criterion within a range does not always vary linearly within the range, hence the range and units should produce a nonlinear characteristic. For simplicity, a linear variation was preferred here. In selecting the acceptable range for units, the "good" end was generally set as the best value that could be expected for designs up to the end of 1968, based on extrapolation of Voyager studies and allied work at General Electric. In some cases it was taken as a desirable limit. The "bad" end was selected as the worst value expected in the realm of acceptable design.

A sample Functional Performance Index Evaluation form is shown as Table 3-8. One of these is prepared for each function of each implementation to be considered. The eleven criteria shown are common to all functions and implementations. Columns noted "Common Measure" are shown. Units and ranges were selected in a manner discussed in detail in our Milestone Reports VOY-D3-TM-14[7] and VOY-D3-TM-22[6]. Units are common to all functions and implementations. Ranges are the same for Separate Subsystem and for Central Computer implementations.

The relative importance of each criterion is expected to be different for each function. Accordingly, a functional weighting allocation (W_f) is indicated for each function. To provide part of the normalization for each evaluation, the summation of W_f's for each function is constrained to be unity.

The remaining three columns of Table 3-8 refer to the particular implementation under consideration. The first column indicates the actual evaluation of the particular criteria (P_m) in units previously identified.

The second column records the normalized penalty associated with that particular implementation. This factor (P_n) is intended to place the performance for each criteria on a common or normalized ground. The P_n's emerge in the range from 0 to 1 with 1 representing the worst penalty. Regardless of the particular method used in its derivation, the P_n factor is intended to reflect a true assessment of performance on a 0 to 1 scale.

The third and last column indicates the weighted normalized penalty for each criterion and is the product of W_f and P_n. The sum of these products is the Weighted Normalized Functional Penalty (P_{en}) which will be a number in the range 0-1. The corresponding Performance Index (P_i) for the function is found by subtracting P_{en} from unity. The index (P_i) then will range from 0-1 with 1 representing best performance for the i^{th} function, and for that particular implementation.

We note that the Separate Subsystem implementations will be relatively straightforward to evaluate as the particular equipment involved will tend to be function unique. In the Central Computer implementations, however, the function will tend to require the use of equipment in common with other functions. The individual P_m's must result from questions such as "With what reliability does the implementation perform the function under consideration?" and "What power is required to perform only the function under consideration?"

3.7.3 EVALUATION OF OVERALL SYSTEM PERFORMANCE

The Functional Performance Index values (P_i) described in Section 3.7.2 indicate relative goodness of implementations of a function. Weighting was done to reflect the importance of a criterion to that function. This section describes how the Total Performance Index (P_T) is derived from the individual P_i values of the functions included in an implementation. Table 3-9 is a sample "Evaluation of Overall System Performance" form.

The Total Performance Index (P_T) is calculated for a system from the expression:

$$P_T = \frac{\Sigma P_i \cdot W_{si}}{\Sigma W_{si}}$$

where:

P_i = functional performance index of function i

W_{si} = system weighting factor for function i

The system weighting factor (W_{si}) is a value from 0 to 1 which represents the estimated importance of a function to the overall system performance. All systems use the same values.

Table 3-9 shows appropriate columns for the quantities discussed and presents in parallel form the values for corresponding separate subsystems S_n and C_n. The P_T values developed on these sheets are compiled and presented in Section 3.8 to show relative merit. The interpretation of relative values is given in Section 4.

Table 3-8. Functional Performance Index Evaluation

Function: Process Ground Commands — Implementation: S1, S4, S7

Criteria	Common Measure: Units	Common Measure: Range (R) Allocated (Note 1)	Functional Weighting Allocation W_f	Evaluation P_m	Normalized Penalty $P_n = [P_m - (P_1 - R)]/R$	Weighted Normalized Penalty $W_f \times P_n$
1. Reliability	Failures/Mission	0 - <u>1</u>	0.68	0.1588	0.1588	0.108
2. Design Difficulty	Hz/Watt / Stage	DIG. $2 \times 10^8 - \underline{2\times10^9}$ ANLG. $10^{15} - \underline{10}^{17}$	0.0	--	--	--
3. Isolation	Note 2	0 - <u>1</u>	0.0	--	--	--
4. Testability GND	% Ckts not testable	0 - <u>100</u>	0.05	0.0	0.0	0.0
5. Testability Space	% Ckts not testable	0 - <u>100</u>	0.05	0.0	0.0	0.0
6. Environment Cont	Note 3	0.1 - <u>1</u>	0.0	--	--	--
7. Power	Watts	4 to <u>40</u>	0.05	16.1	0.30	0.015
8. Complexity/Cost	No. of parts	0 to <u>15000</u>	0.05	15,000	1.0	0.05
9. Flexibility	% (Note 4)	0 - <u>100</u>	0.02	50	0.50	0.010
10. Weight	Pounds	9 to <u>90</u>	0.05	44	0.43	0.022
11. Size	Cubic inches	20 - <u>2000</u>	0.05	1610	0.40	0.020
Weighted Normalized Functional Penalty (P_{en})			1.0			0.23
Performance Index ($1 - P_{en}$)						0.77

Note 1: Worst allowable limit (P_1) is underlined.

Note 2: a/(b+a) where a = number of parts beyond those required to implement the function, outside of those directly related, and b = number of parts for the function (see criterion No. 8)

Note 3: 1 - K, where K is the ratio of actual range of reliable functional operation without special control, to the specified range. 1 - K is averaged over all measure (temperature, pressure, vibration, etc.). Should K exceed unity, it will be taken as unity.

Note 4: The percent of total parts required to preserve critical function.

Table 3-9. Evaluation of Overall System Performance

Function	System Weighting Factor W_{si}	Implementation S_1 (Separate Subsystem)		Implementation C_1 (Central Computer)	
		Functional Performance Index P_i	$P_i \cdot W_{si}$	Functional Performance Index P_i	$P_i \cdot W_{si}$
1. Process Ground Commands	0.9	0.77	0.693	0.68	0.612
2. Provide G&C Logic & Switching Control	0.6	0.89	0.534	0.84	0.504
3. Process Telemetry Data	0.9	0.90	0.810	0.82	0.738
4. Initiate Time-From-Launch Functions	0.3	0.81	0.243	0.64	0.192
5. Initiate Computed Functions	0.3	0.88	0.264	0.67	0.201
6. Initiate Time-To-Go Functions	0.9	0.60	0.540	0.60	0.540
7. Initiate Periodic Orbit Functions	0.6	0.90	0.540	0.77	0.462
8. Provide C&S Data to Telemetry System	0.6	0.88	0.528	0.85	0.510
9. Provide Occultation Signals	0.3	0.79	0.237	0.76	0.228
10. Provide Data Storage Capability	0.6	0.48	0.288	0.48	0.288
11. Perform PSP Gimbal E Local Vertical Tracking	0.6	0.75	0.450	0.80	0.480
12. Provide Control of Experiments	0.9	0.82	0.738	0.84	0.756
13. Process Scientific Data	0.9	0.90	0.810	0.75	0.675
Σ	8.4		6.675		6.186
Total Performance Index $P_T = \Sigma P_i \cdot W_{si} / \Sigma W_{si}$		0.80		0.74	

3.8 COMPARATIVE EVALUATION OF DESIGN APPROACHES

In this task, comparative evaluations were performed for the nine pairs of competitive implementations described in Sections 3.4 and 3.5 and in accordance with the methods described in Section 3.7. Detailed evaluation sheets are included in our Milestone Report VOY-D3-TM-22[(6)].

The results of the evaluation are shown in Table 3-10. It was intended that the primary evaluation be made by direct comparison of the total performance indices for the directly competitive implementations. The immediate result of this comparison is that in all nine cases the performance indices for the Separate Subsystem approach exceed those for the Central Computer approach. In analyzing this result, it is instructive to make comparisons between other than directly competitive implementations. These and other interpretive analyses are discussed in Section 4.

Table 3-10. Indication of Relative Merit

Included Complexity	Applied Redundancy		
	Simplex	Recommended	Maximum
Minimal	S_1, 0.80 C_1, 0.74	S_2, 0.81 C_2, 0.76	S_3, 0.82 C_3, 0.74
Intermediate	S_4, 0.80 C_4, 0.74	S_5, 0.82 C_5, 0.78	S_6, 0.82 C_6, 0.78
High	S_7, 0.79 C_7, 0.73	S_8, 0.82 C_8, 0.79	S_9, 0.82 C_9, 0.75

NOTES: Separate Subsystem Approach Implementations - S_i

Central Computer Approach Implementations - C_i

Numbers are total performance indices having a value from poor at zero to good at unity.

See text for derivation of indices and description of complexity and redundancy degrees.

SECTION 4
INTERPRETATION OF RESULTS

4.1 SIGNIFICANCE OF RESULTS

Overall Performance Indices determined by the study are summarized in Table 4-1.

Table 4-1. Performance Indices

Separate Subsystem Implementations			Central Computer Implementations		
S_1	S_2	S_3	C_1	C_2	C_3
0.80	0.81	0.82	0.74	0.76	0.74
S_4	S_5	S_6	C_4	C_5	C_6
0.80	0.82	0.82	0.74	0.78	0.78
S_7	S_8	S_9	C_7	C_8	C_9
0.79	0.82	0.82	0.73	0.79	0.75

It might first be noted from the table that the spread of values is small, going from $S_7 = 0.79$ to $S_3 = 0.82$, and from $C_7 = 0.73$ to $C_8 = 0.79$. This indicates a tendency of the analysis method to average the factors, and thus to have relatively small sensitivity to any single factor. One possible consequence is that unacceptably low performance in one area, e.g., reliability, might be offset by high performance in weight and power requirements so that the overall rating would be, on the surface, acceptable when in fact the implementation could not be used. Situations of this kind should be caught at the outset, of course, but it illustrates that the comparison gives an indication, but not necessarily the final answer.

The 1973 mission is represented by basic functions on the S_1 S_2 S_3 and C_1 C_2 C_3 levels. As additional functions are added, it will be noted that there is little degradation in going from S_1 to S_4 to S_7; some improvement in going from S_2 to S_5 to S_8; and no degradation in going from S_3 to S_6 to S_9. The center column S_2, S_5 and S_8 represents a modest level of redundancy with a high average value, and while the highest level S_3, S_6, S_9 all have top ratings the cost is also known to be great.

Similarly, the C_1, C_2, C_3 measures are representative of a 1973 mission. Varying redundancy increases from left to right. In going down columns (increasing complexity) it may be noted that the central computer rating remains at about the basic top level value indicating a small increased merit. In examining redundancy levels, one observes that the center vertical column is clearly a standout over the other columns, and would become the recommended form.

A comparison of the S and C values for any corresponding position shows that the C values are consistently lower by more than the spread of the S values.

It is instructive to extract the trends of important parameters from the data. Those considered most important are Reliability, Power, and Weight. These are tabulated and discussed in the following paragraphs. It is important that these, as well as the performance indices, be examined to ascertain the direction parameters will take with a given decision to change complexity or redundancy.

Reliability figures are given in terms of total failures per mission for a mission of 10,000 hours in Table 4-2. For the separate subsystem, the worst failure rate is used for the different functions. For the computer forms, the overall throughput failure rate is estimated.

Table 4-2. Comparative Failure Rate

Separate Subsystems			Central Computer		
S_1	S_2	S_3	C_1	C_2	C_3
0.159	0.039	0.039	0.162	0.129	0.122
S_4	S_5	S_6	C_4	C_5	C_6
0.159	0.043	0.039	0.198	0.140	0.134
S_7	S_8	S_9	C_7	C_8	C_9
0.159	0.093	0.039	0.218	0.151	0.149

The advantages of adding redundancy are demonstrated by the reduction in failure rates going from form 1 to 3, 4 to 6, and 7 to 9. It will be noted that the decrease from 2 to 3 is not as great as 1 to 2 and the gain/cost is open to question. As may be expected when comparing horizontal rows, the failure rate increases with complexity.

A comparison of S and C values shows a consistently higher rate for the central computer. This would justify the choice of a separate subsystem over the central computer if a choice were made on the sole basis of reliability.

Comparisons may also be drawn between the power required for different configurations of S and C. In Table 4-3, the ratings are in watts and the values are peak values. This choice was based on the possible need for solar panels to supply the system without batteries. If the availability of batteries can be assured, average power would be a wiser choice. The advantages of standby-wakeup systems for computers are not reflected here. Power values do not include data storage tape recorders common to both approaches.

Table 4-3. Comparative Power Consumption

S_1	S_2	S_3	C_1	C_2	C_3
102	138	245	42	105	116
S_4	S_5	S_6	C_4	C_5	C_6
108	144	255	47	112	123
S_7	S_8	S_9	C_7	C_8	C_9
123	164	269	49	116	127

By comparing rows, the expected power increases with increased complexity as anticipated, although the proportion of change is not as great for the C forms as for the S forms. A comparison along the rows reflects the increased power with added redundancy in a fairly proportional manner with values for C increasing at a slightly higher rate. A comparison of any C value to a corresponding S value shows the central computer to be an obvious saver of power at all levels.

A comparison on the basis of weight is given in Table 4-4. Weight is in pounds and values do not include weight of the data storage tape recorders.

Table 4-4. Comparative Weight

S_1	S_2	S_3	C_1	C_2	C_3
149	262	347	31	81	88
S_4	S_5	S_6	C_4	C_5	C_6
168	281	388	37	89	97
S_7	S_8	S_9	C_7	C_8	C_9
228	360	510	49	101	111

Weight increases with added complexity and redundancy as might be expected. Added complexity increases weight faster in the separate subsystem approach. A comparison of any C value to an S value shows the central computer to be an outstanding choice on a total weight basis.

4.2 GENERAL APPLICABILITY OF RESULTS

This study was based on the expected near future Voyager requirements, and the present technology, modestly extrapolated, to correspond in time. The basic functions to be performed were selected from past Voyager Tasks B and C with some additions (Science Data Handling) from Task D. The result has been that the expected Voyager 1973. requirements for digital processing differ little from the eleven basic functions of Task B plus Science Data Processing. It was recognized that Voyager 1973 may in the end have more or fewer requirements. In addition, the applicability to later space exploration is to be considered. As a consequence, some functional additions were considered. These were not the most extreme but were believed appropriate to unmanned spacecraft with ground navigation. Spaceborne interplanetary navigation computation was not included as a requirement because for an unmanned vehicle, the degree of sophistication required would probably be an order of magnitude greater. Should such a requirement exist, the case for a central computer would be outstanding. It is believed that data compression and approach guidance are highly probable for advanced Voyager concepts and certainly appropriate for interplanetary exploration beyond Mars, hence they have been included as selectable functional additions.

In any complex unmanned spacecraft, the desirability of some degree of self testing is recognized if it is effective and not too costly. To this end, modest On-Board Check Out was offered as a selectable function. As part of this study, IBM has prepared information on the subject which is appended to our Milestone Report VOY-D3-TM-22[6]. In addition, information was prepared by IBM on the subjects of testing on the ground and on-board, and the testing of computer programs. These data are also appended to the Milestone Report[6]. The information was intended specifically for Voyager but is also, to a high degree, generally applicable.

It is believed that the performance indices reported herein favor the Separate Subsystem approach over a Central Computer approach by a relatively narrow margin. Technological advances with time could well shift the balance of favor. Predicted failure rates for the mid-1970 period, as provided by IBM and appended to our Milestone Report VOY-D3-TM-22[6], forecast an order of magnitude improvement. Greater fabrication simplicity through application of Large Scale Integration (LSI) can be expected. Though benefits will accrue to both separate subsystems and central computers alike, it is entirely possible that the mid-1970 central computer will be sufficiently reliable to represent a clear choice over separate subsystems. The evaluation techniques contained in this report should, if periodically applied, show the trend and time of choice.

4.3 FLEXIBILITY OF COMPARISON METHOD

In addition to being applicable to evaluation of performance for added functions, the comparison method can be used to measure performance with greater sophistication. For example, the weighting factor for power could be made a function of operating power level whereas now it is taken as a constant consistent with expected power level. Absolute limits on some criteria could be recognized. New measures of performance could be developed and applied within the overall framework. Present evaluations were made without the benefit of computer aid; however, the entire numerical evaluation could have been programmed for computer operation. With more refined techniques, computer aid would be required and could be readily applied.

Optimization techniques could be developed, the results of which could be of value in making design tradeoff decisions.

In short, the methods described herein are adaptable to many variations and improvements.

4.4 CONCLUSIONS

Analysis of the details contributing to the evaluation for all cases considered indicates that the effect of economies in power, weight, and size for the Central Computer approach do not fully offset the inherent reliability of the Separate Subsystem approach. These considerations, coupled with engineering judgement based on our experience, lead us to recommend that present Voyager concepts not adopt a centralized computer approach. The relatively small margin by which the separate subsystem approach is favored suggests that for future Voyager missions in which functions of significantly increased complexity may be contemplated, the question can logically be re-opened.

SECTION 5

REFERENCES

1. Larsen, D.P.B. and Skinner, K.L., "Space Packaged Automatic Checkout System," IEEE Trans. Vol. AES-2, No. 4, Supplement, July 1966 pp 777-782.

2. Massey, H.N., and Smith, W.E., "Summary Report, Implementation Investigations of ZVA/FVA Compression Algorithms," Contract NAS8-5110, Accession No. N66-31368, 28 February 1966.

3. Huffman, G., "Error Control Coding for Interplanetary Spacecraft," General Electric Report No. 67SD230, 3 March 1967.

4. Seaman, L.T. and Brown, H.E., "Planetary Approach Guidance for a Martian Mission," presented at AAS Symposium, 12-14 June 1967, Huntsville, Ala.

5. Liviakis, G., and Firstman, S.I., "A Survey of Spaceborne Computers," Technical Advisement Memorandum No. 171-1, PRC D-1237, Planning Research Corporation, Los Angeles, Calif. NASA Accession No. N66-34705.

6. "Indication of Relative Merit" General Electric Voyager Task D Study Milestone Report VOY-D3-TM-22, 28 September 1967.

7. "Preliminary Indication of Relative Merit" General Electric Voyager Task Study Milestone Report VOY-D3-TM-14, 18 August 1967.